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13. ABSTRACT (Maximum 200 words)

The purpose of the research performed on this project was to investigate novel concepts for improving the performance of antennas for use in electromagnetic systems for detecting buried landmines. This research covered four areas: i.) The completion of a theoretical and experimental study of the resistively-loaded vee antenna for use in short-pulse, ground-penetrating radars. ii.) A fundamental study of the coupling between antennas that are very close to the surface of the earth and shallowly buried mines. This study makes use of a plane wave spectral analysis that contains both propagating and evanescent waves. iii.) An investigation of the conical spiral antenna in free space and over the surface of the earth. This antenna has broadband and directive properties that make it particularly attractive for the mine detection problem. iv.) A fundamental study of the transient radiation of electromagnetic energy from simple wire antennas.

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(1) STATEMENT OF THE PROBLEM STUDIED

The purpose of the research performed on this project was to investigate novel concepts for improving the performance of antennas for use in electromagnetic systems for detecting buried landmines. This research covered four areas: i.) The completion of a theoretical and experimental study of the resistively-loaded vee antenna for use in short-pulse, ground-penetrating radars. ii.) A fundamental study of the coupling between antennas that are very close to the surface of the earth and shallowly buried mines. iii.) An investigation of the conical spiral antenna in free space and over the surface of the earth. iv.) A fundamental study of the transient radiation of electromagnetic energy from simple wire antennas. Each of these topics is covered in more detail in the next section.

(2) SUMMMARY OF MOST IMPORTANT RESULTS.

(The numbers after the entries referr to the references listed in the next section)

1. *Resistively-Loaded Vee Dipole Antennas*

Resistively-loaded vee dipole antennas were considered for use in a short-pulse ground penetrating radars designed to detect buried antipersonnel landmines. Earlier, empirical studies by G. Wichmann in Germany indicated that these antennas have desirable properties for this application. Our study involved a complete, three-dimensional, electromagnetic model for the antennas, earth, and buried landmine. This model was analyzed using the finite-difference time-domain (FDTD) numerical method. A limited series of measurements was also performed to verify the analysis.

Parametric studies were conducted using this model in which a number of factors were varied, including: the type of resistive loading, the height of the antenna above the ground, the electrical properties of the ground, and the position and geometry of the landmine. Environmental factors such as variations in the surface of the ground and the presence of clutter in the form of buried rocks were also considered.

The results of this study clearly demonstrated that resistive loading can reduce the clutter caused by reflections internal to the antenna and multiple reflections between the antenna and the surface of the ground. With this reduction in clutter, reflections from buried landmines are evident that would otherwise be obscured. The study also showed that reflections from rocks of the appropriate size and composition can be very similar to those from antipersonnel mines.This effort completed research initiated under the Joint Services Electronics Program (JSEP) by ARO [4].

2. *Antennas for Near-Field Imaging of Buried Objects:*

In some electromagnetic systems proposed for detecting shallowly buried landmines, the antennas are located very close to the surface of the earth. The coupling of energy into and out of the earth can then involve both the evanescent and the propagating waves in the plane-wave spectrum for the radiation. The operating frequency can be chosen so that either the propagating waves or the evanescent waves dominates the spectrum in the range used for imaging the landmine. For the former, the operating frequency (a high frequency) is chosen so that the free-space wavelength is less than the dimensions of the landmine, while for the latter the

operating frequency (a low frequency) is chosen so that the free-space wavelength is much greater than the dimensions of the landmine.

In this research, simple models based on a plane-wave spectral analysis were used to perform a preliminary examination of the role that evanescent waves can play in the detection and identification of landmines. The degree to which features in the image of the landmine can be resolved was of particular interest, since the features can be used to distinguish the landmine from other buried objects, such as rocks. The effect of loss in the soil on imagining was also of interest. The research showed that under the right conditions, the inclusion of evanescent waves in the spectrum can improve the resolution for the location of objects buried in lossy soil [5, 8].

3. *Conical Spiral Antennas over the Earth*

The two-arm, conical spiral is an antenna whose geometry is defined by angles. As such, it has nearly frequency-independent performance over a wide bandwidth. It also has a fairly unidirectional radiation pattern with nearly circular polarization on axis. These characteristics make it attractive for use in ground-penetrating radars that require wide bandwidth.

Dyson carried out the first investigation of the conical spiral antenna (CSA) over 30 years ago. Surprisingly, to date, the only design information for this antenna is Dyson's original, empirically based graphs. So as a first step in this investigation, a full analysis of the CSA in free space was carried out using the finite-difference time-domain (FDTD) method. The analysis was validated by comparison with measurements of the input impedance and the realized gain of model antennas. A parametric study was performed with the analysis, and the results from the study were used to produce new design graphs for this antenna. These graphs supplement and extend the earlier results of Dyson. Two resistive terminations intended to improve the low-frequency performance of the CSA were examined: a pair of lumped resistors connected between the arms at the open end and a thin disc of resistive material connected to the arms at the open end. The latter is a new configuration that was first analyzed in this work. Both terminations were shown to improve the impedance match, front-to-back ratio, and the axial ratio for the CSA at low frequencies but to have negligible effect on the realized gain.

Next, the investigation was focused on understanding the performance of the CSA when placed over the ground, such as in the ground-penetrating radar application. A full FDTD model was constructed for the CSA over a ground containing a buried object. Initially, this model was used to investigate the electromagnetic field near the antenna. The objective was to determine if the desirable characteristics of the far field of the conventional CSA were preserved in the near field, both in free space and within the ground. Over the operating bandwidth of the antenna, the near field was found to be practically circularly polarized and frequency independent (when properly scaled). In addition, the input impedance of the CSA was shown to fairly independent of the reflection from the surface of the ground for a wide range of electrical parameters for the ground.

A parametric was performed to determine how best to configure the CSA for the ground-penetrating radar application. The scattering from buried rods and landmines were investigated. Guidelines for the use of the CSA in ground-penetrating radars were offered [1-3, 9, 10, 12, 13].

4. *Fundamental Studies of the Radiation from Pulse-excited Antennas*

Several ground-penetrating radars proposed for detecting buried landmines make use of pulsed signals. Conventional antenna analysis is generally for time-harmonic excitation, so there is not a wealth of available knowledge about antennas with pulse excitation. This research is aimed at understanding in a fundamental way how simple antennas radiate and receive pulses.

In a recent pedagogical effort, we showed how simple wire antennas with a general excitation, e.g., a pulse in time, can be analyzed easily using approximations no worse than those used with time-harmonic excitation, viz, an assumed current distribution. Expressions were obtained for the electromagnetic field of the current that

apply at any point in space (in the near zone as well as in the far zone). The analysis in the time domain was shown to provide physical understanding not readily available from the time-harmonic analysis. In addition, an interesting analogy was drawn between the radiation from antennas when excited by a short pulse of current and the radiation from a moving point charge.

In a continuation of this effort, we have considered two simple, filamentary current distributions that are frequently used to model practical antennas: the traveling-wave element and the standing-wave dipole. Exact analytical expressions were presented for the electric and magnetic fields of these distributions when the excitation is a general function of time. These expressions apply in both the near and far zones. For an excitation that is a Gaussian pulse in time, exact analytical expressions were obtained for the energy leaving the filament per unit time per unit length, the total energy leaving the filament per unit length, and the total energy radiated. Graphical results based on these expressions were used to study the energy transport from the two filamentary current distributions. The results for the standing-wave dipole were compared with those from an accurate analysis of a pulse-excited, cylindrical monopole antenna performed using the finite-difference time-domain (FDTD) method. The comparison showed the similarities as well as the differences in the energy transport from this simple filamentary current distribution and an actual antenna [6, 7, 11].

(3) PAPERS SUBMITTED OR PUBLISHED:

(a) Manuscripts accepted or submitted for publication, but not published:

1. T.W. Hertel and G.S. Smith, "Analysis and Design of Two-Arm Conical Spiral Antennas," invited paper, to be published in the *IEEE Transactions on Electromagnetic Compatibility.*

2. T.W. Hertel and G.S. Smith, "The Conical Spiral Antenna over the Ground," to be published in the *IEEE Transactions on Antennas and Propagation.*

3. T.W. Hertel and G.S. Smith, "On the Convergence of Simple FDTD Feed Models for Antennas," submitted for publication.

(b) Papers published in peer-reviewed journals:

4. T.P. Montoya and G.S. Smith, "Land Mine Detection Using a Ground-Penetrating Radar Based on Resistively Loaded Vee Dipoles," *IEEE Transactions on Antennas and Propagation*, Vol. 47, PP. 1795-1806, December 1999.

5. G.S. Smith and L.E.R. Petersson, "The Use of Evanescent Electromagnetic Waves in the Detection and Identification of Objects Buried in Lossy Soil," *IEEE Transactions on Antennas and Propagation*, Vol. 48, pp. 1295-1300, Sept. 2000.

6. G.S. Smith, "Teaching Antenna Analysis from a Time-Domain Perspective," *American Journal of Physics*, Vol. 69, pp. 288-300, March 2001.

7. G.S. Smith and T.W. Hertel, On the Transient Radiation of Energy from Simple Current Distributions and Linear Antennas," *IEEE Transactions on Antennas and Propagation Magazine*, Vol. 43, pp. 49-63, June 2001.

(c) Papers published in conference proceedings:

8. G.S. Smith, R.F. Apfeldorfer, and L.E.R. Petersson, "The Role of Evanescent Electromagnetic Waves in the Detection and Identification of Buried Landmines," to be presented at the *SPIE, AeroSense, Detection and Remediation Technologies for Mines and Minelike Targets IV*, 12 pages, April 1999.

9. T.W. Hertel and G.S. Smith, "A Study of the Conical Spiral Antenna for use in Ground-Penetrating Radars: Initial Results," *Detection and Remediation Technologies for Mines and Minelike Targets V*, Proc. of SPIE, Vol. 4038, pp. 1047-1057, April 2000.

10. T.W. Hertel and G.S. Smith, "Analysis and Design of Conical Spiral Antennas using the FDTD Method," *IEEE Antennas and Propagation Symposium Digest*, Vol. 3, pp. 1540-1543, Salt Lake City, UT, July 2000.

11. G.S. Smith, "Teaching Antenna Analysis from a Time-Domain Perspective," Digest (CDR) for the *Millennium Conference on Antennas and Propagation*, 4 pages, Davos, Switzerland, April 2000.

12. T.W. Hertel and G.S. Smith, "The Conical Spiral Antenna over the Ground," *Detection and Remediation Technologies for Mines and Minelike Targets VI*, Proc. of SPIE, Vol. 4394, pp. 730-741, April 2001.

13. T.W. Hertel and G.S. Smith, "On the Convergence of Simple FDTD Feed Models for Antennas," *IEEE Antennas and Propagation Symposium Digest*, Vol. 2, pp. 76-79, Boston, MA, July 2001.

(d) Ph.D. Dissertations:

14. T.W. Hertel, "Analysis and Design of Conical Spiral Antennas in Free Space and over Ground," Ph.D. Dissertation, Georgia Institute of Technology, Atlanta, GA, November, 2001.

(4) SCIENTIFIC PERSONNEL:

Dr. Glenn S. Smith, Regents' Professor and John Pippin Chair in Electromagnetics
Dr. Thorsten W. Hertel, Graduate Research Assistant (Earned Ph.D. while working on this project)
Mr. L.E. Rickard Petersson, Graduate Research Assistant (Ph.D. Candidate)
Mr. R.F. Apfeldorfer, Graduate Research Assistant.